NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION
PATUXENT RIVER, MARYLAND

REPORT OF TEST RESULTS

REPORT NO: NAWCADPAX/RTR-2003/122

TEST RESULTS OF AN F/A-18 AUTOMATIC CARRIER LANDING USING SHIPBOARD RELATIVE GLOBAL POSITIONING SYSTEM

by

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DEPARTMENT OF THE NAVY
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14. ABSTRACT

Under the U.S. Department of Defense's Joint Precision Approach and Landing System program, the Navy is responsible for developing the shipboard component, termed Shipboard Relative Global Positioning System (SRGPS). As part of the SRGPS effort, a test bed was developed to demonstrate air traffic control, navigation, and landing capabilities in the carrier environment. During flight testing from January through April 2001, Global Positioning System (GPS)-based automatic landings were conducted at NAS Patuxent River, Maryland, and aboard the USS THEODORE ROOSEVELT (CVN-71) using an F/A-18A Hornet test aircraft.

This report describes the overall SRGPS test effort. The report also gives an overview of the test bed hardware, as well as results for navigation sensor error, flight technical error, and total system error. The test and analysis results support the feasibility of the GPS-based precision approach and landing system concept.

15. SUBJECT TERMS

Shipboard Relative GPS (SRGPS), JPALS, Landing System, Automatic Precision Approach

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SUMMARY

Under the U.S. Department of Defense's Joint Precision Approach and Landing System program, the Navy is responsible for developing the shipboard component, termed Shipboard Relative Global Positioning System (SRGPS). As part of the SRGPS effort, a test bed was developed to demonstrate air traffic control, navigation, and landing capabilities in the carrier environment. During flight testing from January through April 2001, Global Positioning System (GPS)-based automatic landings were conducted at NAS Patuxent River, Maryland, and aboard the USS THEODORE ROOSEVELT (CVN-71) using an F/A-18A Hornet test aircraft.

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Contents

List of Figures

List of Tables

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The SATNAV team would like to acknowledge the outstanding support from AIRLANT and the personnel from the USS THEODORE ROOSEVELT, without whom this demonstration would not have been possible.

INTRODUCTION

BACKGROUND

1. Joint Precision Approach and Landing System (JPALS) is a revolutionary, next generation, Precision Approach and Landing System (PALS) under development by the Department of Defense (DoD). JPALS includes both the sea-based variant, Shipboard Relative Global Positioning System (SRGPS) - which provides precision navigation and two-way Air Traffic Control (ATC) for sea-based aircraft operations - as well as the local differential systems for providing precision landing capability ashore. The SRGPS will support all ATC functions including takeoff, departure, taxi, marshal (holding), approach, landing, bolter, missed approach, and long-range navigation as shown in figure 1. SRGPS will be compatible with Naval Emissions Control requirements and the associated avionics provide complete interoperability with DoD, Allied, and civil navigation systems. In addition to supporting manned aircraft, SRGPS will fully support automatic takeoff, departure, approach, landing, and ATC automation required by future unmanned systems such as the Naval Unmanned Combat Air Vehicle.

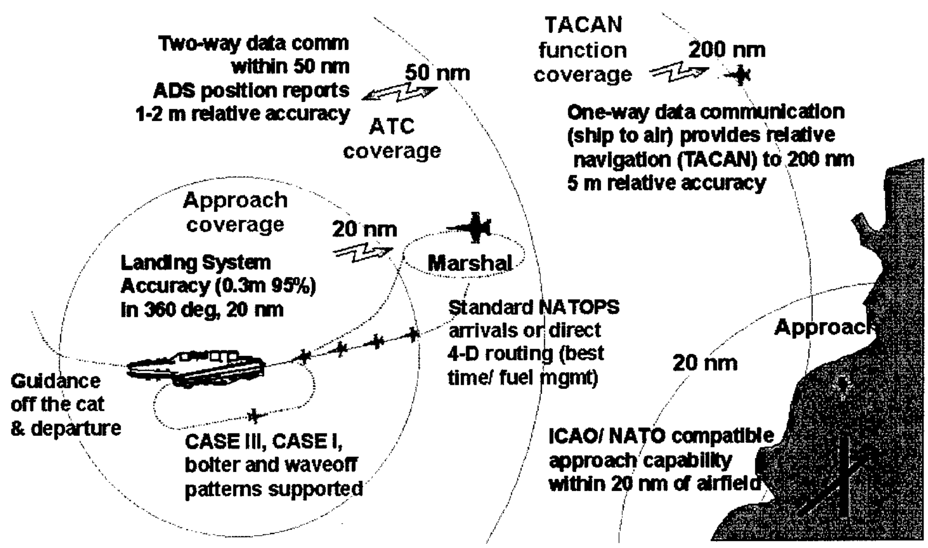

Figure 1: SRGPS Concept

2. SRGPS shares some basic concepts with local differential Global Positioning Systems (GPSs) used ashore (such as the FAA's Local Area Augmentation System (LAAS)), but with a few important differences. Any local differential DGPS relies on the fact that relative measurements between two GPS receivers in the same local geographic area can be made very accurately. When the solutions of two receivers utilizing the same satellites are compared, common mode errors such as satellite clock, satellite ephemeris (orbit errors), and atmospheric transmission errors, generally cancel out. This comparison of two GPS receiver's measurements of one satellite is termed a *single difference*. Since one ground system is meant to serve multiple aircraft, a technique was developed where the ground system broadcasts *differential corrections* to all aircraft. Each aircraft uses only those corrections that correspond to valid satellite measurements in its own receiver. In addition, these corrections would be made to a surveyed

point, resulting in not only an accurate relative solution, but also an accurate absolute position (in the GPS coordinate frame, WGS-84). To use this accurate position for navigation, the glidepath (defined by a set of path points) and waypoint data are sent to the aircraft via the data broadcast.

3. In the SRGPS concept, the "reference station" is installed on a ship instead of a fixed surveyed point in the WGS-84 coordinate frame. The GPS antenna location(s) aboard ship are precisely surveyed in the ship body axis relative to the inertial system locations, the ship's center of motion, and the aircraft touchdown point. This ensures that accurate relative vectors are maintained as the ship translates through the water, pitches, rolls, and yaws around its center of motion. In addition, the center of motion itself may translate up/down (heave), side to side (sway), and fore and aft (surge). Any location away from the center of motion (such as the GPS antenna location, or aircraft touchdown point) will experience additional heave, sway, and surge due to the lever arm effect. Despite this motion, a single difference calculation between a ship antenna and aircraft antenna can be made just as accurately as its shore-based counterpart. The primary difference is simply that the differential correction technique is not used, since absolute positioning accuracy is not required.

4. Instead of a correction, the shipboard GPS transmits whole satellite measurements to the aircraft and the aircraft directly compares aircraft and ship solutions based on a common set of satellites. This method produces an accurate relative vector between the two antenna locations, which are further translated to the ship and aircraft centers of motion and the reference flightpath points. For tailhook equipped aircraft, the hook point is intended to touchdown halfway between the second and third arresting gear wires on the ship. These translations are made through the use of precision Inertial Navigation System (INS) measurements on the ship and the aircraft.

5. In addition, unlike the shore approach, the ship flightpath is calculated in a dynamic fashion. The approach path is stabilized for ship motion until approximately 10 sec (0.3 nmi) from touchdown. At this point, the aircraft is commanded to follow the touchdown point sway and heave motions during the final portion of the approach. This portion of the approach is termed the Deck Motion Compensation phase. The aircraft is controlled in reference to an approach heading that is based on a filtered cant deck heading to allow for ship turns and yaw motions during the aircraft's approach.

6. The safe landing area aboard ship is much smaller than runways at major airports. Aircraft landing off centerline by more than 3 m (~10 ft) laterally can result in the aircraft's wingtip being dangerously too close to obstructions on the flight deck. The aircraft's hook path over the end of the landing area, termed the hook to ramp clearance, is only 4.3 m (~14 ft). The most demanding requirement for a shore-based LAAS system is 2 m (~6.5 ft) of vertical navigation system error to accomplish an automatic landing. Aboard ship, 2 m of vertical error would result in an unsafe landing condition. The SRGPS requires 0.4 m (~1.3 ft) vertical error to accomplish a safe automatic landing. Figure 2 shows a 1.5 sec time lapse of an aircraft arrestment, showing both the wire locations and the ideal touchdown point.

Figure 2: Aircraft Carrier Landing

7. To meet the requirement for shipboard landings, further refinements to the standard single difference technique were made. A double difference calculation is made where all satellite measurements at both receivers are also compared against a key satellite. The double difference solution is smoothed in a Kalman filter and the resulting solution is termed the float solution. From this float solution, a carrier phase integer ambiguity determination is made using the LAMDA method developed by Teunissen, reference 1.

PURPOSE

8. The purpose of these tests was to demonstrate SRGPS landing system performance integrated in the carrier-landing environment. These tests were primarily for data gathering to support the Architecture Requirements Definition phase of the JPALS program and are not intended to fully evaluate a system for fleet release.

DESCRIPTION OF TEST PLATFORM/SYSTEMS

SHIPBOARD RELATIVE GLOBAL POSITIONING SYSTEM HARDWARE OVERVIEW

9. Figure 3 shows the relationship of the various SRGPS system hardware components.

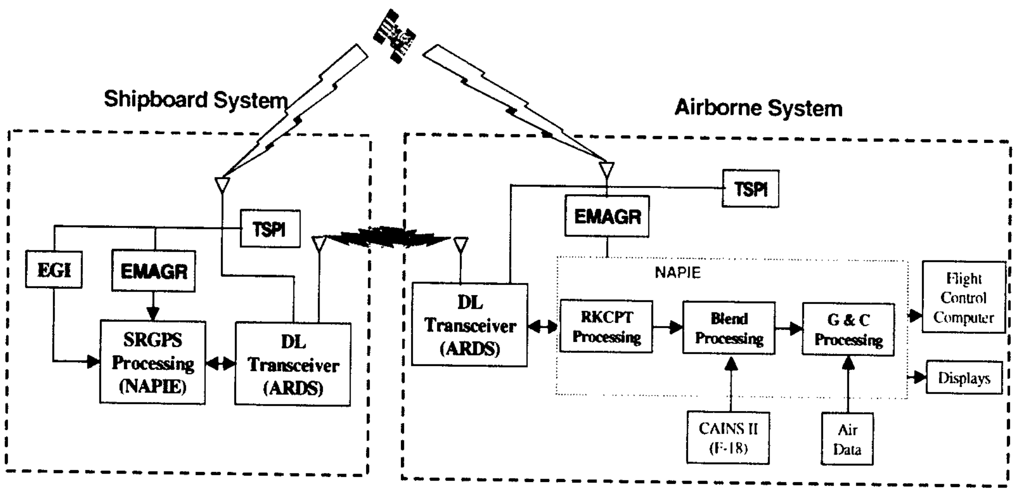

Figure 3: SRGPS Hardware Diagram

Naval Avionics Platform Integration Emulator

10. The Naval Avionics Platform Integration Emulator (NAPIE) is designed to facilitate rapid prototyping and development of new avionics concepts. In generic form, the NAPIE installation consists of a rugged commercial-off-the-shelf computer, a data recorder, an interface to the host-aircraft's avionics busses, and an interface to the system under test. NAPIE is designed to emulate devices in the host aircraft, thus allowing prototype equipment to be integrated into the aircraft in a production-representative fashion. NAPIE eliminates the need to modify the operational software of the existing host aircraft mission computer. Changes to the cockpit displays and flight controls (external to the aircraft's Flight Control Computer) can be made through NAPIE, thus cutting the time and expense that would otherwise be required to support an early flight-test demonstration or system development program.

11. For this test effort, there were two NAPIE computer systems used. The airborne unit hosted the system operation, control and display, Relative Kinematic Carrier Phase Tracking (RKCPT), and guidance and control algorithms. The shipboard NAPIE hosted the Ship Motion Sensor algorithms and preprocessed shipboard GPS data for uplink to the aircraft.

Enhanced Miniaturized Global Positioning System Airborne Receiver

12. The Enhanced Miniaturized Airborne GPS Receiver (EMAGR) from Rockwell Collins was the primary GPS sensor used in the SRGPS airborne and shipboard subsystems. The EMAGR, shown on the left in figure 4, is a 24-channel (12 L1 channels and 12 L2 channels) GPS receiver designed for airborne applications. The EMAGR provided the SRGPS system with raw Y-code pseudorange and carrier phase data, all in view, for both L1 and L2 frequencies simultaneously. EMAGR output messages received by SRGPS (airborne and shipboard) were recorded for postflight analysis. The quality of the SRGPS position solution critically depended on the quality of the data provided by the EMAGRs. Aboard ship, the data quality was primarily affected by the type and location of the shipboard antenna.

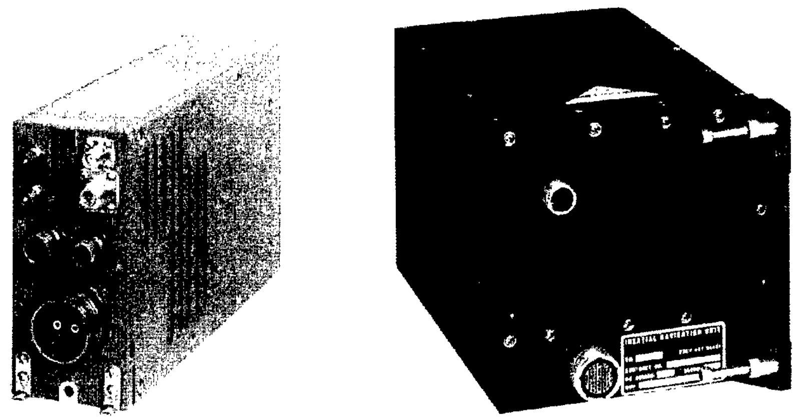

Figure 4: Rockwell EMAGR and Litton Embedded GPS INS (EGI)

Embedded Global Positioning System Inertial Navigation System Navigation Unit

13. The inertial sensor used in the shipboard subsystem was the Litton AN/ASN-172 EGI, (figure 4, right), which is a strap-down INS. The EGI is composed of inertial navigation components and a GPS receiver housed in the same chassis, using a common power supply. The EGI provides both free inertial navigation outputs and outputs whose errors are bounded by the outputs from the GPS receiver (see reference 2). The free inertial performance is classified as medium accuracy (0.8 nmi/hr drift rate and velocity errors of 2.5 ft/sec). The blended output has a stated accuracy of 10 m or better with velocity accuracy of better than 0.05 ft/sec.

14. The inertial components include three orthogonally mounted Zero Lock Gyros® and three orthogonally mounted accelerometers. The GPS receiver is a five-channel single module that is fully militarized and capable of receiving both L1 and L2 GPS signals and can operate on C/A, P, and Y codes. The EGI is mechanized with two separate redundant MIL-STD-1553 busses, one of which is solely for independent GPS operation. The primary bus provides communication with both the inertial navigation portion of the EGI, as well as the GPS receiver.

Advanced Range Data System

15. The SRGPS datalink used was a customized version of the Advanced Range Data System (ARDS) datalink system. The SRGPS datalink operated in dual-frequency mode in L-band in the range 1350-1400 MHz or at the discrete frequency of 1433 MHz. The transmitter power was nominally 80 W, and the range was approximately 90 nmi. The datalink used a Time Division, Multiple Access architecture.

16. The baseline ARDS configuration consisted of a ground segment and an air segment. The ground segment comprised an L-Band datalink antenna, a Data Link Transceiver (DLT), a Ground Station Interface Unit, a Data Link Control/Data Link Processor computer, and a PC display station. The air segment consisted of an L-Band datalink antenna, a DLT, and an Advanced Digital Interface Unit that interfaced to NAPIE and the aircraft data system.

Antennas

17. Three Fixed Radiation Pattern Antenna (FRPA) L1/L2 GPS antennas were used: a standard Navy shipboard antenna AS-3819, a Sensor Systems antenna mounted on a flat ground plane, and a MicroPulse antenna with an integral choke ring ground plane. Figure 5 shows these three antennas in order from left to right and their locations as mounted on the upper yardarm of the ship. During shipboard testing, data were collected from all three antennas with the choke ring antenna used as the primary antenna for the majority of the flight testing. Each antenna used the same Delta Microwave GPS Diplexer/Amplifier.

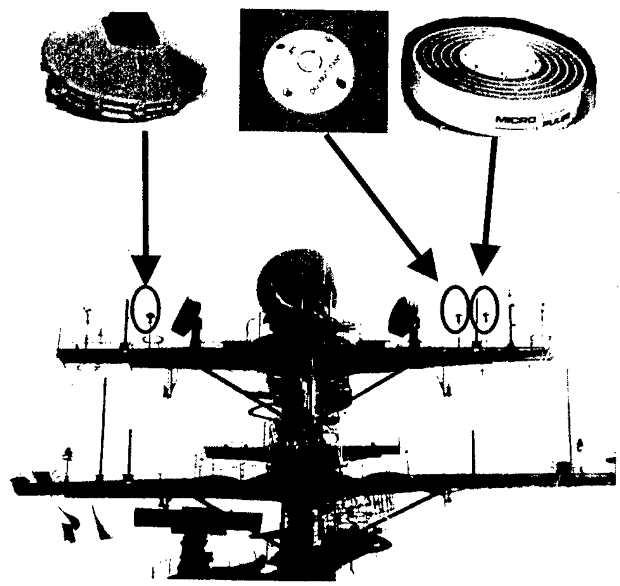

Figure 5: Shipboard GPS Antenna Installation

Time Space Position Information

18. Raw NovAtel L1/L2 GPS data were taken on both the ship and aircraft for postflight comparison to the SRGPS data. On the aircraft, the NovAtel was connected to the same GPS preamp output as the SRGPS. On the ship, the NovAtel was connected to the same GPS preamp output for the antenna that was being used for a particular flight test event.

Shipboard Relative Global Positioning System Test Aircraft

19. A single F/A-18A was the test vehicle for the SRGPS demonstration. The F/A-18A is a single-place fighter/attack aircraft, which incorporates an Automatic Carrier Landing System (ACLS) auto-land capability currently in use by the fleet. The specific aircraft for these tests was a Lot 9 F/A-18A, from the Air Test and Evaluation Squadron 23 (VX-23) designated SD110 (BuNo 163148) at NAWCAD Patuxent River, Maryland. The test aircraft with modifications and instrumentation was otherwise fleet representative.

AIRBORNE INTEGRATION

20. Modifications to the aircraft included an instrumentation pallet, containing all aircraft SRGPS/NAPIE hardware, which was loaded in the test aircraft's gun bay. Externally, two L-band data link antennas were installed – one on the "turtleback" behind the canopy, and one on the "chin" of the aircraft. A standard Navy Dorne & Margolin L1/L2 FRPA GPS antenna was installed in the aircraft's turtleback in the same location as in the production F/A-18C/D's. Figure 6 shows the location of the SRGPS equipment on the flight test aircraft, the instrumentation pallet, and the pallet being uploaded for flight. A particularly useful feature of the system integration was that once the instrumentation pallet was loaded on the aircraft, all interfaces were accessible through the gun access door as can be seen in the lower right picture of figure 6. Removable PCMCIA flash memory cards were accessible through this door and were used both for software upload as well as data recording.

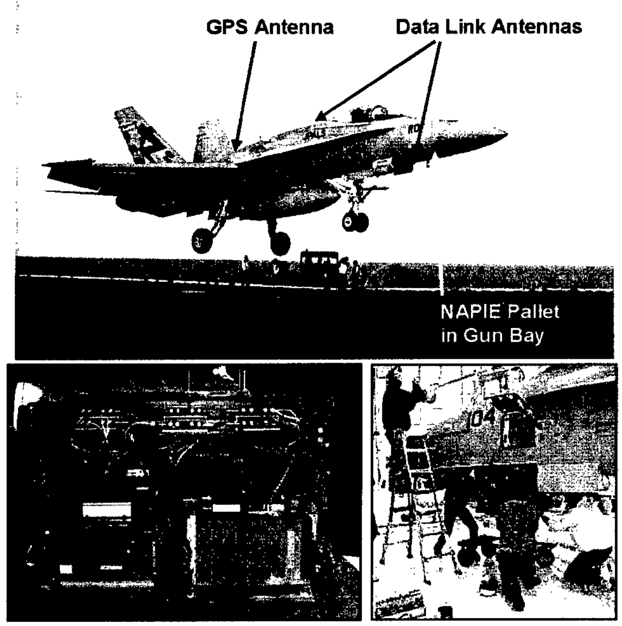

Figure 6: F/A-18 Installation and SRGPS Pallet

21. The NAPIE computer was mounted on an F/A-18 instrumentation pallet, and interfaced with the host-aircraft avionics through a network of 1553 bus relays. The bus relays either isolate NAPIE or place NAPIE "in the loop" between the Mission Computer and the host avionics. The pilot could isolate the NAPIE system from the aircraft system at any time in flight through a master switch for all bus relays, which returns the aircraft to the normal production aircraft configuration. This installation is made fail-safe by ensuring the bus relays always fail to the NAPIE "isolate" position. Figure 7 shows the SRGPS/NAPIE airborne hardware integration in the aircraft.

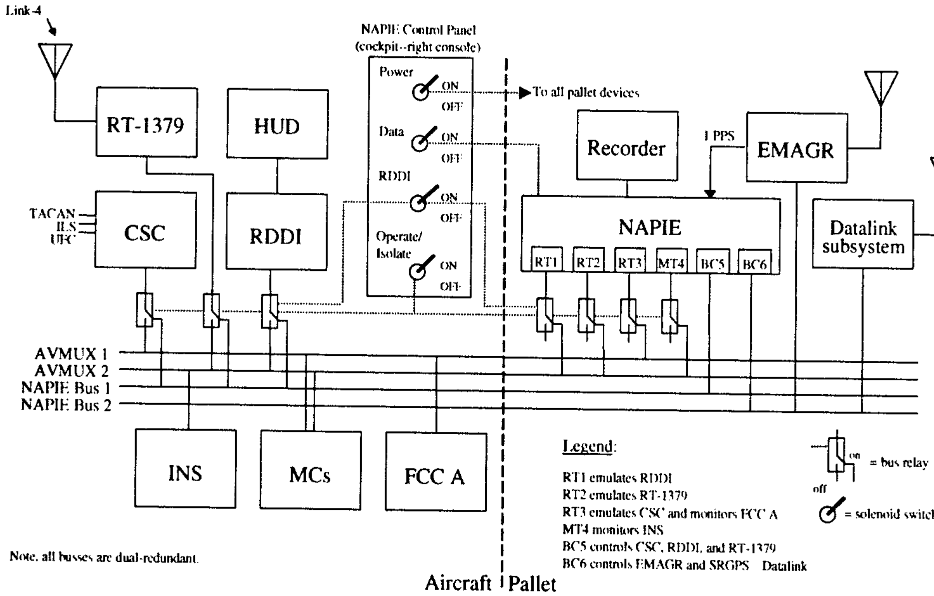

Figure 7: Aircraft/Instrumentation Pallet Diagram

22. NAPIE emulated the production ACLS RT-1379 datalink radio in order to send guidance information and autopilot commands based on the SRGPS solution to the F/A-18 Mission Computer. Similarly, NAPIE also emulated one of the cockpit displays - the Right Digital Display Indicator (RDDI) - for pilot control and display of system performance parameters. One of the NAPIE RDDI pages is shown in figure 8.

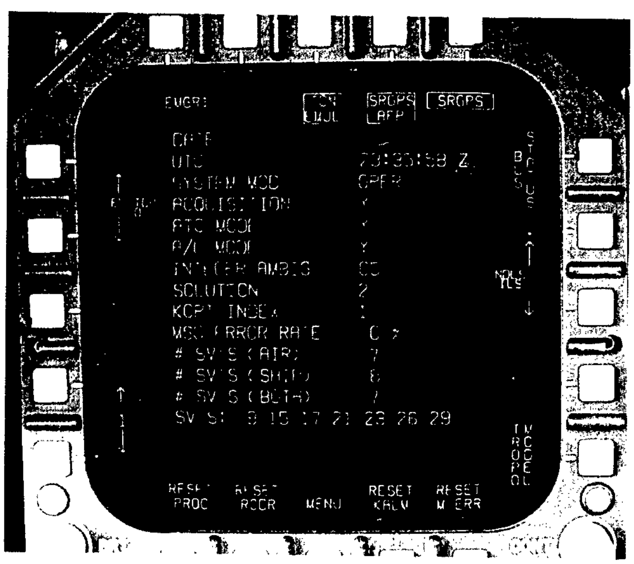

Figure 8: NAPIE Emulated RDDI

23. In addition to the cockpit displays, NAPIE overdrove the Head-Up Display (HUD) in the aircraft with SRGPS symbology. SRGPS initially used the same guidance symbology as ACLS. Flightpath deviations are depicted graphically on the HUD as a tadpole symbol (ȯ) referenced to

a velocity vector symbol (-ȯ-) as shown in figure 9. The horizontal and vertical position of the tadpole relative to the velocity vector corresponds to the horizontal and vertical deviations from the programmed flightpath. For example, a tadpole above and to the right (as shown in figure 9) of the velocity vector meant that the aircraft was below and to the left of the programmed flightpath. Tadpole deflections represented angular deviations from flightpath and were scaled linearly throughout the tadpole's range. A full-scale horizontal deflection corresponded to a horizontal deviation of 6.0 deg or greater. A full-scale vertical deflection corresponded to a vertical deviation of 1.4 deg or greater.

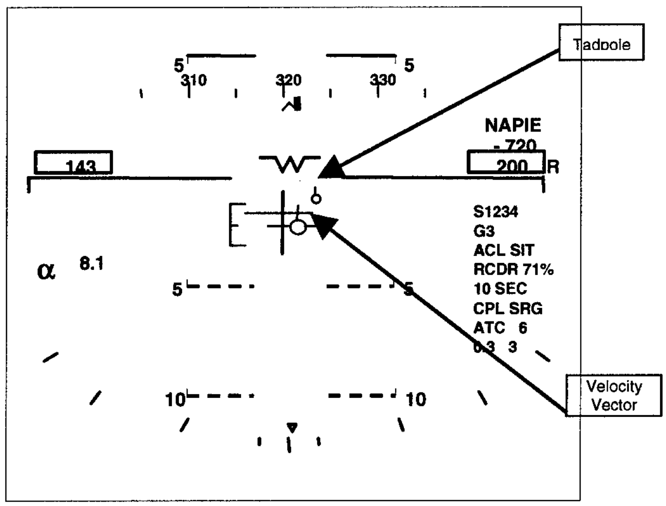

Figure 9: SRGPS/NAPIE HUD Illustration

24. In addition to the tadpole situation display, the SRGPS was also capable of driving a flight director display described in more detail in reference 3.

SHIPBOARD INTEGRATION

25. The SRGPS shipboard station consisted of a ARDS two-way L-band data link transceiver, an EMAGR, a Time Space Position Information (TSPI) truth receiver, an EGI, a real-time controller and a system performance parameters display with NAPIE as the central processor, as shown in figure 10.

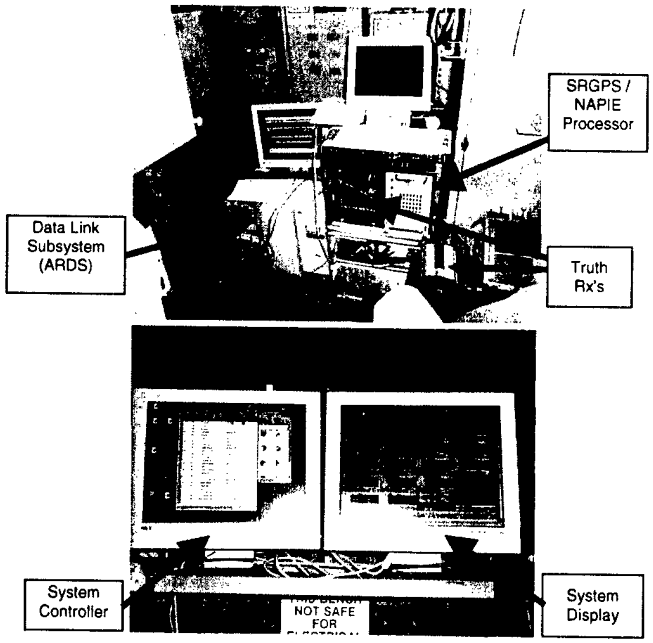

Figure 10: SRGPS Shipboard Station

26. The ground station collected, processed, and up linked the GPS wide-lane data, ship motion and stabilization measurements to the airborne system as shown in the functional diagram, figure 11. For additional information on the guidance and control processing used for SRGPS testing, see reference 3.

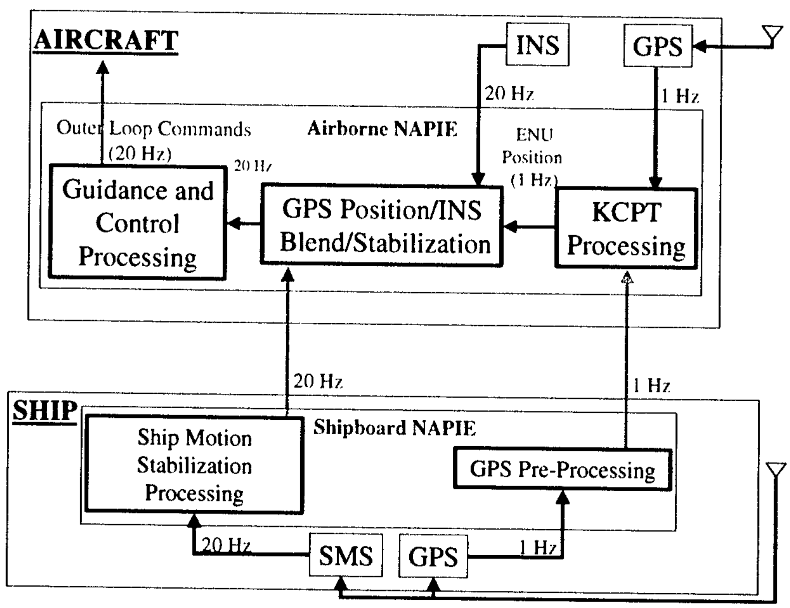

Figure 11: SRGPS Functional Diagram

SCOPE/METHOD OF TESTS

27. A total of 19 flights and 23.1 flight-hours was flown during a 3-month period between 30 January and 27 April 2001. Shore-based testing was conducted at NAS Patuxent River, Maryland, and shipboard testing was conducted aboard the aircraft carrier USS THEODORE ROOSEVELT (CVN-71) underway in the Atlantic Ocean.

28. Prior to at-sea testing, initial test flights of the SRGPS system were flown ashore. A total of 8 flights ashore totaling 8.3 hr was flown to verify, assess, and improve system performance; to test and modify various guidance and control law gains; to evaluate aircraft open and closed loop response to SRGPS commands; and to test control volume and control limiters in aircraft pitch and roll.

29. The external loading of the aircraft was limited to one configuration of a single 330-gal external fuel tank mounted under the aircraft along the centerline. No other external stores or pylons were used during test flights. The intent was to limit the aircraft's configuration to a well-defined aerodynamic and inertial model, one well supported with historical performance data.

30. Both manual and automatic SRGPS approaches were flown during tests. Manual approaches were flown with the pilot following SRGPS commands displayed in the HUD. Once satisfactory performance was observed during manual approaches, subsequent approaches were flown with the aircraft's autopilot engaged to follow SRGPS commands. Initial automatic approaches were first flown to elevated touchdown points safely between 100 and 400 ft above the ground and/or ship where the touchdown point was moved up along the glidepath. Additionally, Mode IA (manual takeover at 200 ft above touchdown) approaches were conducted to verify system alignment with the touchdown point. It was not until at least one of each of these approaches demonstrated satisfactory SRGPS performance, that automatic approaches to touchdown on the runway or flight deck were performed. Each software change effecting guidance and control required the same buildup for safety.

31. All flight periods were conducted in daylight visual meteorological condition. Shipboard wind-over-deck (WOD) averaged 25 kt at 357 deg relative and varied from 23 to 26 kt and 347 to 005 deg relative to the keel.

32. All automatic SRGPS approaches at sea were flown with the aircraft's arresting hook up to avoid the risk of in-flight hook engagement of the arresting gear in case pilot takeover was necessary over the wires. During SRGPS testing at sea, changes in aircraft attitude were unremarkable and pilot takeover could be managed during all test conditions. Based on the effectiveness of the system limiters and the ability for pilot takeover, the hookup test safety requirement will be reexamined for future testing.

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DATA ANALYSIS

33. The data collection, reduction, and analysis performed during this test effort were designed to demonstrate the feasibility of shipboard approach and landing. Data analysis was also critical for the identification and correction of any noted system anomalies or deficiencies. For each test, analysis began by assessing the performance of sensors that were integrated into the SRGPS system. The postprocessed GPS TSPI data were assessed to determine its suitability as a baseline against which the SRGPS system could be judged. In addition, the SRGPS performance was compared to the ACLS tracking during the approach. Finally, carrier landing system performance metrics were evaluated for the overall SRGPS system.

TIME SPACE POSITION INFORMATION

34. For comparison to the RKCPT and blend guidance position outputs, raw NovAtel GPS data at 4 Hz were postprocessed using GrafNav to generate the TSPI. Default GrafNav settings for kinematic base station and rover data with dual frequency measurements were used, and time forward, time reverse, and variance weighted combined forward-reverse solutions were saved.

35. Performance of this TSPI was analyzed to determine its availability and expected accuracy. Since the TSPI solution was based on the same GPS constellation as the RKCPT solution, it was expected that, at times, both would be showing degraded performance. For example, when the GPS satellites being tracked were affected by high angle of bank maneuvering, sometimes one or both solutions had trouble maintaining their most accurate solution (or any solution if less than four satellites were tracked). A significant difference in the two solutions, however, was that the RKCPT solution was calculated in real-time while the TSPI solution was postprocessed. In postprocessing, one may take advantage of knowing which satellites are continuously tracked for all times in the data (past, present, and future) and of processing techniques such as forward-reverse averaging. Therefore, it was expected that the TSPI solution would have better performance on average than the RKCPT solution and could be used to calculate the accuracy of the RKCPT solution, or the Navigation Sensor Errors (NSE). However, the TSPI had one significant disadvantage in tracking the P-code with a codeless technique, resulting in a lower signal-to-noise than the Y-code tracking of the EMAGR. In cases where the TSPI data were judged to be experiencing degraded performance, the truth data were declared unavailable and no NSE was calculated.

36. In addition to position and velocity of the aircraft relative to the ship, estimates of the solution accuracy (residuals), the number of satellites used in the solution, and a general quality factor were generated to support analysis of the postprocessed solution. For the position solution to be considered acceptable, the solution residual must have been less than 10 cm, the number of satellites used in the solution must have been 4 or more, and the quality factor must have been 2 or less (on a scale of 1 to 6 with 1 being the best). Typically, between 5 and 10% of the truth data were deemed to have unacceptable performance for a given approach.

37. Several specific differences were noted between the RKCPT solution and the postprocessed forward-reverse combined NovAtel solution. These differences generally were less than 0.5 m but at times were as large as 1 to 2 m. When noted, these differences also existed between one of the forward or reverse processed solutions, and hence the combined solution as well. The GRAFNAV software's averaging of the two processed solutions may be very useful in other applications, but in SRGPS the averaging of these different solutions generally induced a TSPI bias in the data. For carrier phase systems, the errors are assumed to be integer multiples of the wavelength. Theoretically, if there are two different TSPI solutions, either one of them is right and one is wrong, or they are both wrong – but both cannot be "right". It was noted that when the TSPI solution differences occurred, the single direction solution with the lowest residual was much more consistent with the RKCPT output than the other. The fact that these relatively small differences were noticed at all highlights the relatively good performance of the real-time RKCPT solution. The fact that the exact determination of RKCPT accuracy is difficult emphasizes the challenge in demonstrating system integrity.

38. In addition to the NovAtel derived TSPI, SRGPS coupled approaches were also tracked with the standard shipboard precision approach radar, the ACLS - AN/SPN-46. While the stabilized coordinate frames of the SRGPS and AN/SPN-46 can be substantially different at range, the alignment converges as the aircraft nears the touchdown point. The AN/SPN-46 tracking data, along with both pilot and Landing Signal Officer comments, were used to corroborate the NovAtel TSPI. From these combined sources, average alignment of the SRGPS approach path was determined. NSE was calculated using the 4 Hz TSPI data and blend guidance position outputs from the SGRPS. For coupled approaches, Flight Technical Error (FTE), or how well the aircraft flew the approach path, was also calculated.

SYSTEM PERFORMANCE ANALYSIS

39. SRGPS performance during flights conducted on 23-24 April 2001 aboard the USS THEODORE ROOSEVELT was analyzed in some detail and a portion is presented here. During these flights, the Navy performed its first fully automated approach and landing to the deck of an aircraft carrier using relative GPS for guidance.

40. On these 2 days, there were a total of 17 SRGPS approaches made. Fifteen of the 17 approaches had data suitable for analysis. For 10 of these 15 approaches, automatic control was provided to touchdown on the deck. In this report, ensemble FTE and NSE results for the 10 completed approaches are presented.

RUNWAY COORDINATES

41. SRGPS NSE and FTE were analyzed in a canted deck (runway-oriented) coordinate system. This runway coordinate system was right-handed and orthogonal with the origin at the desired touchdown point, the x-y axis plane level with the earth at this touchdown point, and the x-axis positive aft (positive with increasing distance from touchdown). The y-axis was positive starboard of the touchdown point, and the z-axis was positive in the up direction.

NAVIGATION SENSOR ERROR DATA

42. The SRGPS navigation sensor error is shown in figure 12. Data during the last mile of the approach are presented as typical for the entire approach. NSEs in the three runway coordinate directions are plotted as functions of the distance of the hook from the touchdown point in nautical miles. Errors are plotted in feet, where positive (+) is up, right, and aft (this sign convention holds for all FTE, NSE, and Total System Error (TSE) data presented).

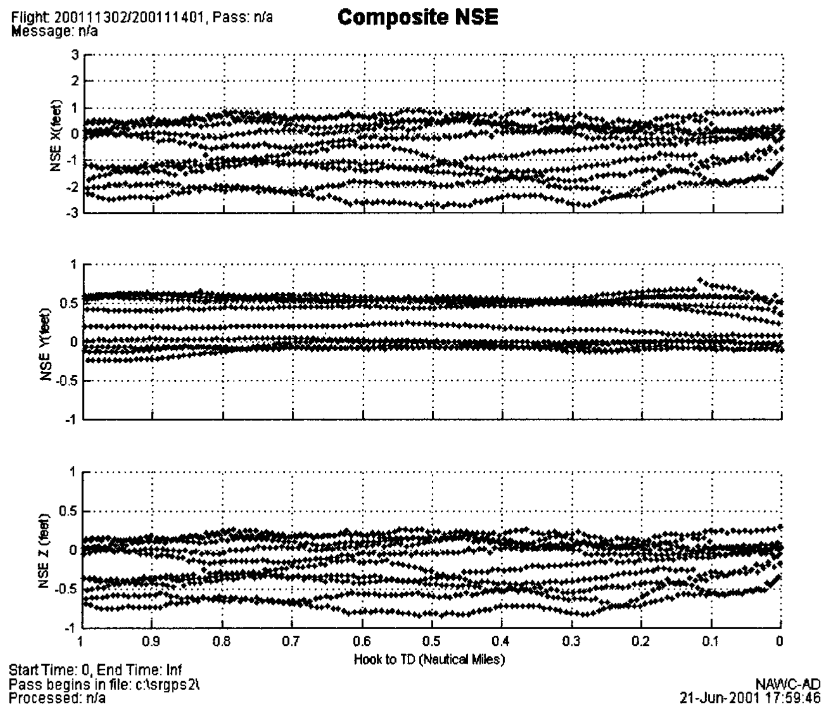

Figure 12: Composite NSE Plot

43. When evaluating NSE, the SRGPS time tag and TSPI time tag were aligned. It should be noted that the SRGPS time tag was always latent 100 msec by design, based on the most recent airborne INS measurement. This latency is part of the overall control system latency and was compensated for when calculating NSE.

44. Table 1 shows the mean and standard deviations of the NSE as a function of range from touchdown. The data have been grouped into 15 bins. Each bin is 0.0667 nmi wide so the bins cover the range from 0 to 1 nmi. At the typical 200 ft/sec approach speed of the aircraft, the bins equate to approximately 2 sec wide.

Table 1: NSE Statistics

Distance from TD (nmi)	0.97	0.90	0.83	0.77	0.70	0.63	0.57	0.50	0.43	0.37	0.30	0.23	0.17	0.10	0.03
Y error mean (ft)	0.26	0.27	0.27	0.26	0.29	0.27	0.28	0.27	0.27	0.25	0.25	0.27	0.26	0.26	0.23
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.27	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.27
Z error mean (ft)	-0.23	-0.21	-0.21	-0.18	-0.19	-0.18	-0.18	-0.18	-0.20	-0.20	-0.20	-0.21	-0.15	-0.15	-0.11
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
X error mean (ft)	-0.74	-0.70	-0.69	-0.59	-0.64	-0.60	-0.60	-0.59	-0.64	-0.64	-0.67	-0.70	-0.50	-0.50	-0.37
X error std dev (ft)	1.02	0.99	0.97	1.02	0.99	1.06	1.08	1.13	1.13	1.04	1.13	1.01	0.86	0.86	0.76

45. The NSE mean in the last mile averaged 0.26 ft in lateral (Y), -0.19 ft in vertical (Z), and -0.61 ft in longitudinal (X). Standard deviations averaged 0.28 ft in Y, 0.31 ft in Z, and 1.00 ft in X. The X direction has some residual time uncertainty, but the Y and Z direction have mean plus one standard deviation values of 0.54 ft (16 cm) and 0.50 ft (15 cm), respectively, over the last mile. At touchdown, these values are 0.50 ft (15 cm) and 0.35 ft (11 cm) for Y and Z, all of which meet the intended accuracy requirement for SRGPS. A portion of the mean and standard deviation contribution appears to be a function of the truth receiver operation as described previously; this is under investigation.

FLIGHT TECHNICAL ERROR DATA

46. Figure 13 shows composite Y and Z FTE from the automatic control system with statistics given in table 2.

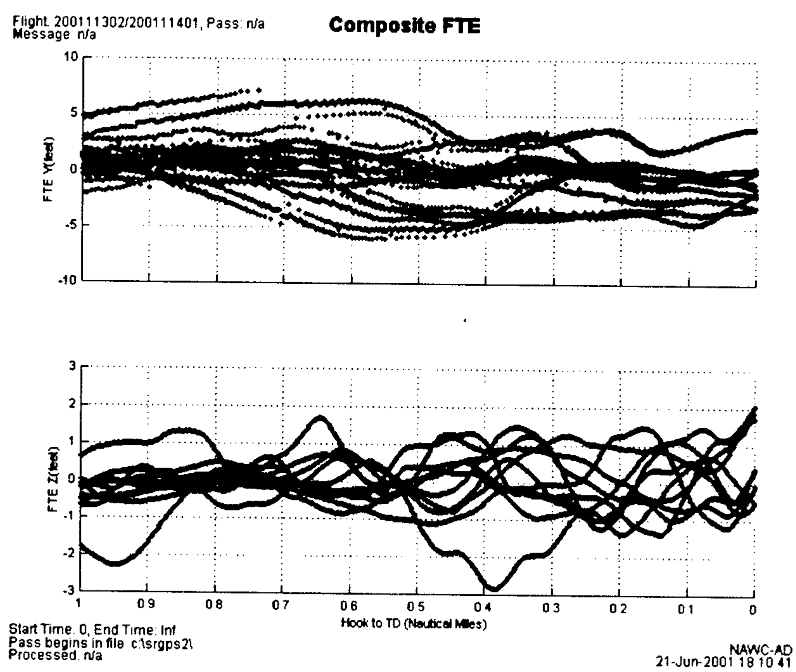

Figure 13: Composite FTE Plot

Table 2: FTE Statistics

Distance from TD (nmi)	0.97	0.90	0.83	0.77	0.70	0.63	0.57	0.50	0.43	0.37	0.30	0.23	0.17	0.10	0.03
Y error mean (ft)	0.87	1.08	1.12	0.93	0.62	0.16	-0.26	-0.63	-0.90	-0.47	-0.25	-0.47	-0.92	-1.10	-0.92
[illegible]	1.54	1.61	1.89	2.20	2.56	2.87	3.06	2.86	2.56	2.40	2.25	2.13	1.86	1.90	1.98
Z error mean (ft)	-0.33	-0.14	0.05	0.04	0.08	0.11	-0.11	-0.14	-0.05	0.09	-0.04	-0.28	-0.03	0.17	0.27
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

47. The SRGPS maintains very tight control during the last mile of the approach. The mean Y and Z FTE averaged over the last mile are –0.08 and –0.02 ft, with average standard deviations of 2.24 and 0.68 ft, respectively. This is well within the desired performance of ACLS. Note that there is some trending in the FTE data. Notice a slight trend in Z, for example, to fly through the glide slope right near touchdown in a low to high manner. Also note the tendency to move slightly left near touchdown. Since the approaches were conducted in relatively consistent wind conditions, the aircraft's response to the burble results in some trending of the FTE along the approach although the mean FTE is near zero. The burble, and the resultant trending, will be a direct function of the carrier WOD magnitude and direction.

TOTAL SYSTEM ERROR DATA

48. Table 3 shows the TSE data calculated from NSE and FTE for just the lateral and vertical data (since FTE is not calculated for X). TSE average standard deviation is within 2 ft for lateral and 1 ft for vertical control.

Table 3: TSE Statistics

Distance from TD (nmi)	0.97	0.90	0.83	0.77	0.70	0.63	0.57	0.50	0.43	0.37	0.30	0.23	0.17	0.10	0.03
Y error mean (ft)	1.13	1.35	1.39	1.19	0.91	0.43	0.02	-0.36	-0.63	-0.22	0.00	-0.21	-0.66	-0.84	-0.69
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.57	2.42	2.27	2.15	1.86	1.92	1.98
Z error mean (ft)	-0.56	-0.35	-0.16	-0.14	-0.11	-0.08	-0.29	-0.32	-0.24	-0.11	-0.25	-0.49	-0.18	0.01	0.16
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

TOUCHDOWN DISPERSION DATA

49. Because the approaches were flown hook up, several methods were used to estimate the hook touchdown point. A primary method in use for many years during ACLS verifications is a visual spotter for longitudinal touchdown. The spotter notes the main wheel touchdown point and then subtracts 25 ft (in the case of the F-18 and nominal pitch attitude) for the hook offset. These estimates were further refined by taking the actual main gear to hook offset for each approach as calculated from the pitch attitude data from the INS. The data are shown in table 4.

Table 4: Observed Touchdown Performance

Date/ Pass	Observed Main Wheel Touchdown Wire	Feet from Wire	Main Wheel from TD (ft+ long)	Hook from TD (ft+ long)	INS estimate
23-Apr					
Pass 2	3	-5	15	-7.21	20.94
Pass 3	3	25	45	17.82	9.56
Pass 5	4	0	60	39.15	36.53
Pass 6	3	-15	5	-21.63	-23.26
24-Apr					
Pass 2	3	10	30	2.87	6.53
Pass 3	3	15	35	6.27	16.47
Pass 4	3	-10	10	-18.76	-12.26
Pass 5	3	15	35	8.37	15.65
Pass 7	4	-5	55	34.56	29.86
Pass 8	3	20	40	19.5	42.86
		Mean	33.00	8.09	14.29
		Standard Deviation	18.44	20.44	20.55
without pass 6/8		Mean	35.63	10.38	15.41
		Standard Deviation	17.61	19.65	14.95

50. A second method was used to estimate touchdown point using the SRGPS and INS data and is described in reference 3. The results of this analysis in the longitudinal direction are shown in the right-hand column of table 4. In addition, both longitudinal and lateral estimated hook touchdown points are plotted in figure 14 in relation to the arresting gear wires and the commanded touchdown point. Figure 14 shows the landing area to scale, where the arresting wires are 40 ft apart and symmetrically placed about the desired touchdown point. Most of the projected touchdown points are in good agreement with the visual data, except for Pass 2 of 23 April 2001 and Pass 8 of 24 April 2001, where the INS-GPS method estimated touchdown points over 20 ft longer than the visual data.

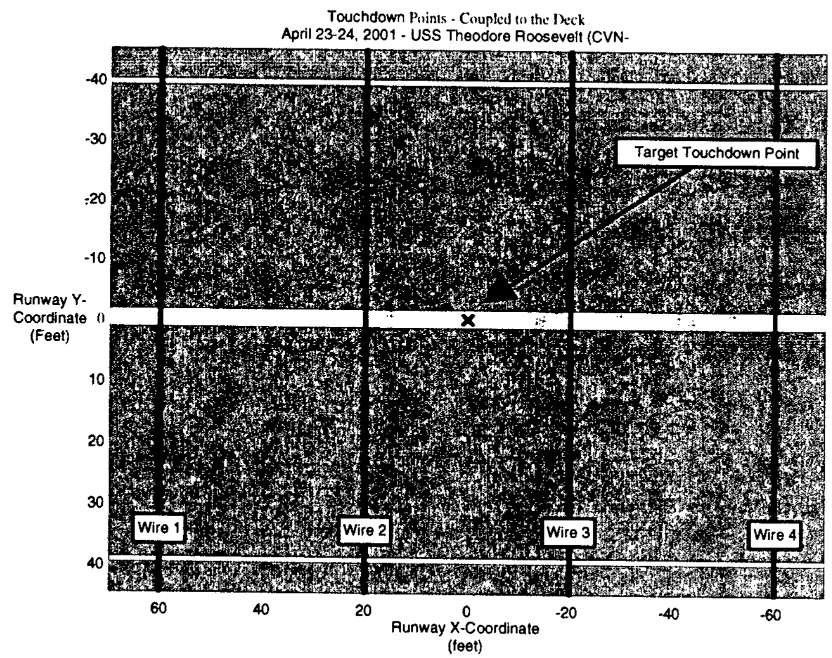

Figure 14: Estimated Touchdown Performance from SRGPS Data

51. In order to compare touchdown performance to ACLS, a common control program baseline must be obtained. Since Pass 6 of 23 April 2001 and Pass 8 of 24 April 2001 used different control program settings, they were removed from the touchdown performance estimates in the subsequent analysis described in reference 3. For these eight approaches, the estimated arresting hook touchdown points averaged 15.4 ft long and 1.4 ft starboard of centerline laterally with dispersions of 15 ft and 1.1 ft, respectively.

52. The SRGPS touchdown statistics exceed the requirements for Navy PALS certification as shown in table 5.

Table 5: Estimated Touchdown Performance of SRGPS versus PALS Certification Requirements

	Certification Target	Not To Exceed	SRGPS Results
Lateral Mean	2	4	1.4
[redacted]			
Longitudinal Mean	16	24	15.4
[redacted]			

53. For aircraft carrier automatic landings, the touchdown dispersions are more important than the average touchdown location, because the average touchdown location can be corrected by adjusting the geometry constants in the SRGPS. Overall, results indicate very good performance that is equal to or better than typically seen with the current ACLS. However, the sample size is very limited, the deck motion was quite small and winds over the deck were nominal at 25 kt during the SRGPS demonstration.

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CONCLUSIONS

54. Ten successful GPS-based automatic landings were completed aboard USS THEODORE ROOSEVELT, demonstrating very good touchdown and glide slope performance. During the at-sea test period, data were collected to support the further development of SRGPS for the shipboard environment.

55. The SRGPS flight testing demonstrated the feasibility of operating a GPS-based automatic landing system aboard ship.

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3. Guidance and Control for Shipboard Automatic Landing using GPS – E.C. Schug, J.W. Aksteter, R.W. Huff, M. Smith - Proceedings of the 57th Annual Meeting of the Institute of Navigation, Albuquerque, New Mexico, of 11-13 Jun 2001.

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APPENDIX A
LIST OF TEST TEAM MEMBERS

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LCDR Jack Waters, Test Pilot

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Lee Wellons, Lead Data Analysis Engineer (4.11.3.3)

John Zander, F/A-18 Integration Engineer (4.11.3.3)

Howard Beaver, SATNAV T&E SIPT Lead (4.11.3.3)

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Brian Thorward, Lead NAPIE Software Engineer (4.5.1.2)

Jason Wosniac, NAPIE Software Engineer (Lockheed Martin)

Dick Huff, Lead Guidance and Control Engineer (SNC)

Eric Schug, Guidance and Control Engineer (SAIC)

John Weir, Senior Data Analysis Engineer (J.F. Taylor, Inc.)

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